MONITORING FREEZE-THAW ALONG NORTH-SOUTH AI, ASK AN TRANSECTS USING 1)I{ S-1 SAR

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ABSTRACT

Monitoring freeze-thaw transitions of the soil and vegetation in high latitude terrestrial ecosystems is useful for determining the length of the growing season, and for monitoring potential damage to living plants due' to freezing and frost drought. We present a technique for monitoring freeze-thaw cycles using repeat-pass SAR data from the European Remote Sensing Satellite, ERS-1, 100 km in swath width, and mosaicked together along a North-South Alaskan transect 1400 km in length. Freezing of the soil and vegetation is detected based on a 3 dB decrease in radar cross-section σ^o relative to a known thawed state of the landscape. The decrease in σ^o is explained by radar backscatter models as resulting from a large decrease of the dielectric constant of the soil and vegetation with freezing. The technique is validated using air-temperature recordings from 3 forest stands along the Tanana River near Manley Hot Springs, and from local weather stations along the transect. The technique does not apply to areas of standing water, but is independent of the type of vegetation cover, and permits the spatial and temporal monitoring of freezing of the natural landscape at the regional scale.

INTRODUCTION

Freezing and thawing play a major role in high latitude ecosystems. Freezing and frost drought result in potential damage for living plants and have a profound effect on the natural distribution of vegetation types and their proliferation [1]; freezing and thawing dissipate more than half of the annual energy balance in the Arctic [?], and dominate the energy balance during spring break-up and fall freeze-up; and 1, freezing strongly modulate the length of the growing season, which is important to monitor for estimating annual productivity in the boreal forests and in the tundra, and for understanding the interactions between land and atmosphere and biogeochemical cycles [3].

A technique for estimating the length of the growing season is to assume no photosynthesis occurs when air-temperatures drop below -2°C [4]. Surface temperatures may be estimated from thermal infrared emissions, but the measurements are limited by cloud cover and are only available at IO-day to one month intervals. Freezing rates may also depend on tree species, e.g. white spruce trees show a rapid response to fluctuations in air. temperature while balsam poplar trees, because of their higher concentration of sugars, take several days to freeze. Freeze/thaw patterns are also affected by elevation, and exposure to the sua, suggesting that measurements directly related to phase changes Of the water content of the soil and vegetation would be better than proxy indicators such as air or surface temperature.

At microwave frequencies, freezing results in a dramatic drop of the dielectric constant of the soil and vegetation equivalent to that of a sudden drying of the soil and vegetation since the liquid water content of frozen soil and frozen vegetation is very small. For very wet soil and vegetation, the real part of the dielectric constant is $\epsilon_r \approx$ 30- 40, whereas for frozen/dry soil and vegetation, $\epsilon_r \approx$ 3- 4 (e.g. [5]). Freezing therefore corresponds to the most dramatic change in the dielectric properties of natural terrain, and should be readily detected by SARs.

ERS-1 SAR DATA SET

ERS-1 operates a SAR instrument at C-band frequency, VV-polarization, 23° look angle, with a 100 km swath, and at 30 m nominal resolution [G]. During the 1991 Commissioning Phase (08/03 - 12/15), ERS-1 followed a sun-synchronous polar orbit at a mean altitude of 785 km with an exact 3-day repeat cycle. Fig. 3 shows the descending repeat-track of ERS-1 that intercepted with the city of Manley Hot Springs at about 1:00 pm Alaska daylight time. The data collected by ERS-1 over that transect in 1991 were processed, and calibrated by the Alaska SAR Facility (ASF) at the University of Alaska's Geophysical Institute in Fairbanks, Alaska [7]. The calibration accuracy is about 1 dB, and the radar gain stability is reportedly better than 0.33 dB [8].

Using repeat-pass SAR data present several advantages. The incidence angle of the radar illumination is repeated within fractions of a degree during every pass, so geometric distortions induced by the imaging geometry and topographic variations are exactly repeated, co-registration of the data is limited to the determination of a single pixel offset [9], and changes in σ^o can be analyzed directly from slant-range imagery. If changes are analyzed using the ratio of the σ^o values, they are independent of radiometric calibration errors [10] and of topographic Variations.

Mosaicking ERS-1 repeat-pass SAR images together is yet complicated by various types of geometric distortions in the SAR data that vary along track due to altitude and Earth velocity changes within the 100 km² scene [1 1], resulting in registration errors in the overlapping segments of consecutive images. These errors are not visible in the SAR mosaics, but they appear distinctly during change detection, e.g. in mountainous terrain.

EXPERIMENTAL RESULTS

Air-temperatures were collected in 3 tree stands in a forest silt near Manley Hot Springs, 150 km West of Fairbanks, and were also provided by 7 weather stations within the ERS-1 transect. Fig. 3 shows a decrease in σ^o of about 3 dB in a black spruce stand between DOY (day of year) 270 where air-temperatures are warm and DOY 290 where air-temperatures are several degrees below freezing. A decrease of about the same magnitude was observed in balsam poplar, white spruce, and tree-less stands. We interpret this decrease in σ^o using the MIMICS radar backscatter model as resulting from a large decrease in the dielectric constant of the soil and vegetation with freezing [12]. A similar decrease in σ^o was measured for bare soils using a scatterometer [1 3].

To detect freezing we therefore compute the ratio of the σ^o values in reference to a known thawed state of the vegetation. The landscape is frozen when the decrease in σ^o is larger than 3 dB. In this study, the technique is applied to an entire North-South Alaskan transect. The reference thawed date is DOY 224 (Rev. # 384, August 12, 1991) because air-temperatures were then warm and above zero all across the transect. The results of the change detection technique are shown in Fig. 2. Freezing is first detected on DOY 254 North of the Brooks Range, and slowly propagates through the southern latitudes until 1)0% 320 when almost the entire transect is in frozen state.

Fig. 4 show average radar back scatter values extracted from homogeneous areas (20 pixels^2 area, 2 km^2 in size) within a few kill of the 7 weather stations. In Prudhoe Bay, freezing temperatures occur early in the year and yield a 5 dB decrease in σ^o on 1)0% 272. After 1)0% 290, snow covers the ground, and σ^o increases by a few dB, but the change is not due 10 thawing but probably to scattering from large depth hoar crystals [1 2], At Bettles, σ^o drops by more than 3 dB on 1)0% 280 when air-temperatures are several degrees below zero. Similar results are obtained in Tanana with a 3.5 dB decrease in σ^o on 1)0% 290, and in Lake Minchumina with a 4 dB decrease on DOY 290. Freezing conditions in Farewell Lake Lodge on DOY 280 result in a decrease in σ^o larger than 3 dB on DOY 290, followed by a war in period which likely thawed the landscape, yielding a 5 dB increase in σ^o on DOY 302. After DOY 302, cold temperatures returned, resulting in a decrease in σ^o smaller than 3 dB, suggesting that freeze-up was not complete on DOY 320. Freezing conditions are reported on DOY 312 in Port Alsworth, resulting in a 3 dB decrease in 0° on 1)0% 320. The observations in Iliamna are similar. In summary, the freeze detection algorithm appears applicable over a large range of latitudes and over many cliff event landscapes.

σ^o from river channels and standing lakes in the Arctic Plains do not decrease between DOY 224 and DOY 320, and are in fact often increasing. This increase can be doc to refraction of the radar signals at the air/ice interface, a shorter effective wavelength of the signal in ice compared to air, and scattering by a rough ice/water interface and air-bubbles inclusions [14]. All these factors concur to increase σ^o. Grounded frozen lakes in contrast undergo a decrease in 0° [14]. The change detection technique is therefore not applicable to areas of standing water.

In the high regions of the Brooks Range, σ^o does not change because the terrain is already in a frozen state on DOY 2'24. With air-temperatures about 2°C in Prudhoe Bay (elev. 24m) on DOY 224, and based on a dry adiabatic lapse rate of 10(per 100 m, subzero air-temperatures already reigned above 224 m elevation on DOY 224, i.e. most of the Brooks Range. A similar situation is encountered in the Alaska Range.

Recently burned areas appear clearly in the ERS-1 SAR imagery (Fig. 2a) due to an increase in forward scattering through tree-t1 unk/ground double reflections [1 5]. σ^o takes longer to decrease and reach a stable value in those areas, indicating that recently burned areas take longer to freeze. Interestingly, when a fire burns in a northern black spruce forest underlained by permafrost, the active layer thickness increases, not because of the heat of the fire, but due to the removal of the insulating organic material which lowers the sur face albedo and decreases shading effects of the tree canopy [1 6]. Hence, the slower decrease in 0° of these areas is likely due to a thicker active, layer in these areas. This example illustrates the dependence of freezing rates on the amount of soil moisture in the soil profile as discussed in [17-18], and shows that repeat-pass SAR imagery could detect differences in freezing rates,

CONCLUSIONS

Despite an extreme variability in vegetation cover across the transect, detecting areas of freeze at the regional scale using ER - 1 SAR appears promising, independent of the vegetation cover, us. ing change detection techniques. Freezing rates however depend on the type of surface cover, and topographic variations of several hundreds of meters cannot be ignored during detailed analysis of the detected changes, suggesting that ancillary information is required to help interpret the radar observations. Monitoring freeze/thaw using SAR data could however help determine the length of the growing season within a few days, over large areas, and study its dependence on species, elevations, and sun illumination. Daily rates of change in radar backscatter could also help

estimate freezing rates.

In this study, we addressed changes in the water status of the boil and vegetation considered as a single medium which undergoes large freeze-thaw cycles, because single-channel radar observations are not likely to separate the contribution from different layers of the landscape and for example determine which of the soil or vegetation freezes or thaws first. Combining ERS-1 data with SAR data at another frequency could help separate these different effects. Finally, monitoring freeze/thaw is more essential during spring break-up because this tillc, period is most critical to the start of the growing season, but we did not have enough data to analyze that period. In principle, σ^o should increase, following an increase in the dielectric properties of the terrain, but the electromagnetic response of the surface could be complicated by the presence of melting snow into various spatial patterns, and by the rapidly transforming and growing vegetation, so that changes in 0° may be associated to more than one facto].

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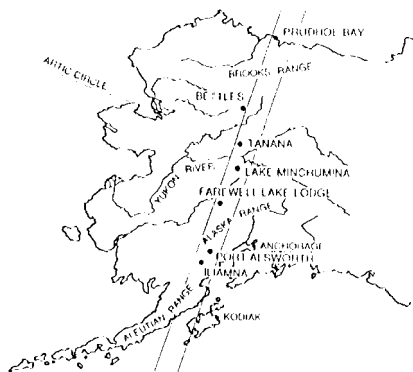
Figure 1. Map of Alaska showing the location of the descending ERS-1 North-South transect during the 1991 Commissioning Phase that intersected with the city of Manley Hot Springs
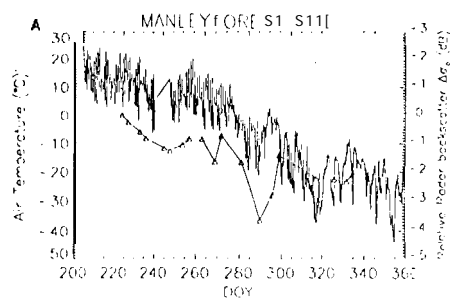
Figure 3. Air temperatures recorded in a black spruce stand near Manley Hot Spring.. along with the ERS-1 σ^o values.
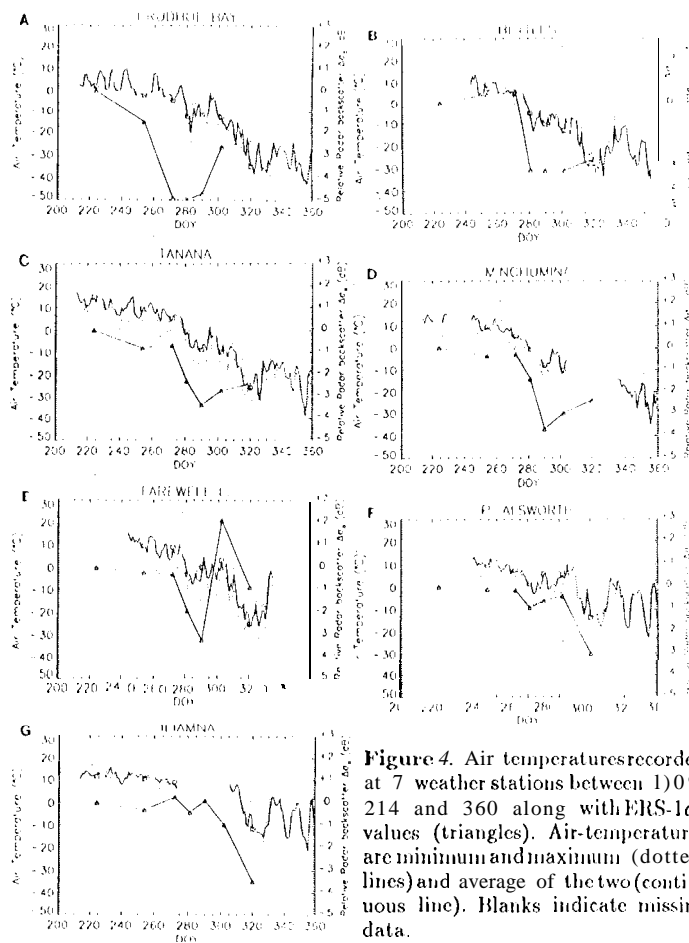
Figure 4. Air temperatures recorded at 7 weather stations between 1) 0% 214 and 360 along with ERS-1 σ^o values (triangles). Air-temperatures are minimum and maximum (dotted lines) and average of the two (continuous line). Blanks indicate missing data.
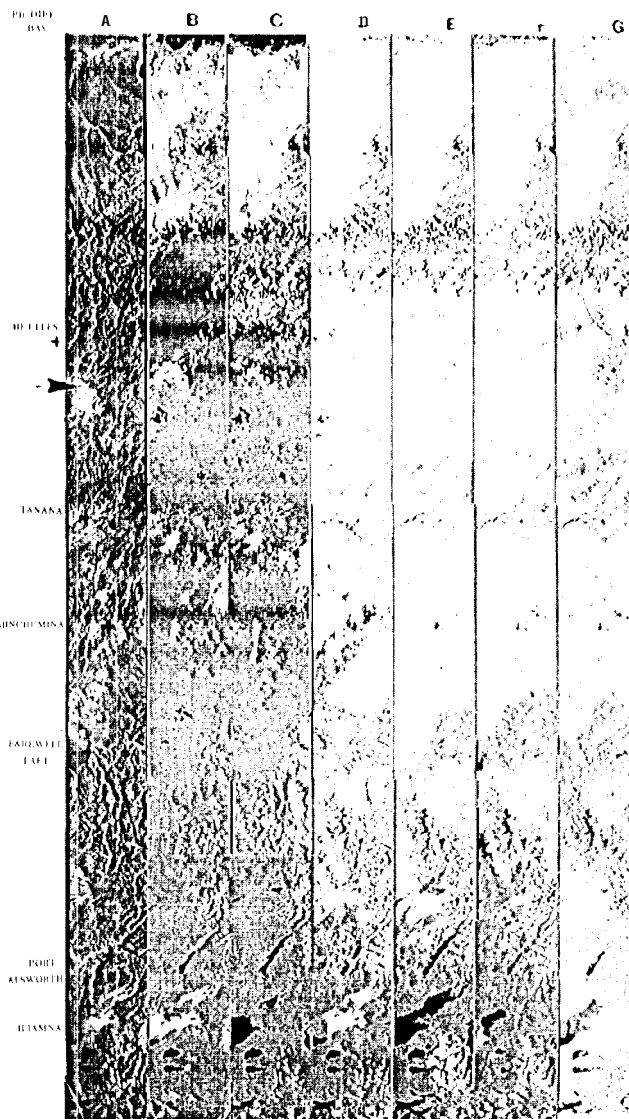
Figure 2. North-South Alaskan transects acquired by ERS-1 SAR during the 1991 Commissioning Phase at 1:00pm Alaska daylight time. North is to the top, ERS-1 flying from top to bottom looking to its right. Each transect is 100 km x 1400 km in size, 100 min pixel spacing. (a) Amplitude image for Rev #/ 384, DOY 224 (reference thawed date). '-I ' symbols mark the location of 7 weather stations along the transect. (c-g) Change detection maps for Rev #814(DOY 254), 1072 (DOY 272), 1201 (DOY 281), 1330 (DOY 290), 1502(DOY 302), and 1760 DOY (320) between -3 dB (white) and +3 dB (black). Areas where σ^o decreases by more than 3 dB are colored white, areas that do not change by more than 3 dB are colored grey, and areas where σ^o increases by more than 3 dB are colored black. A black arrow below Bettle shows a recently burned area. ©ESA, 1991,